Single π^0 production in MINERνA using Medium Energy beam

(A first approach on energy resolution)

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New Perspectives
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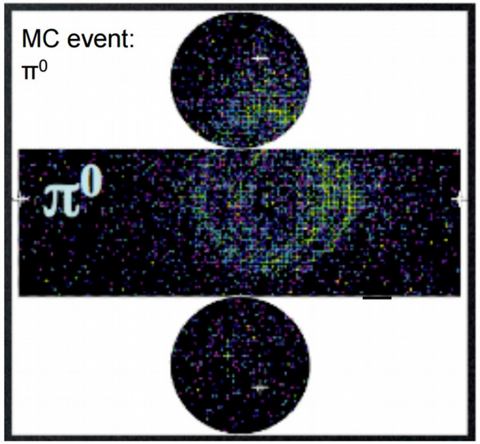
Why study neutrino π^0 production?

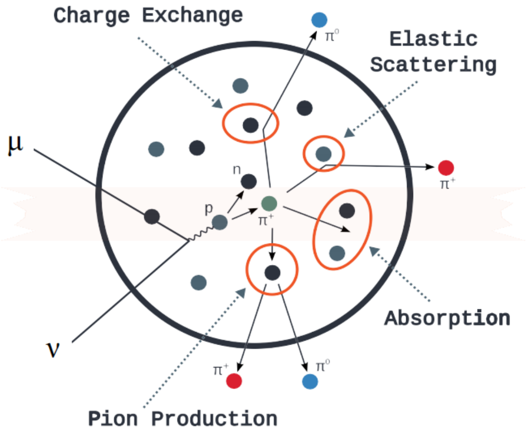
Neutrino-nucleus cross sections in the range of 1-20 GeV are important for experiments like NOνA and DUNE since they need an understanding of neutrino interactions for their oscillation measurements.

Neutrino-induced π^0 production processes that are background for oscillations:

- Neutral-current π^0 can mimic a final state electron/positron in (anti)neutrino electron appearance.
- Charged-current π^0 and absorption in the nucleus can mimic quasi-elastic signal.

T2K simulation of NC π^0 background
K. Mahn – Fermilab JTEP – July 2015





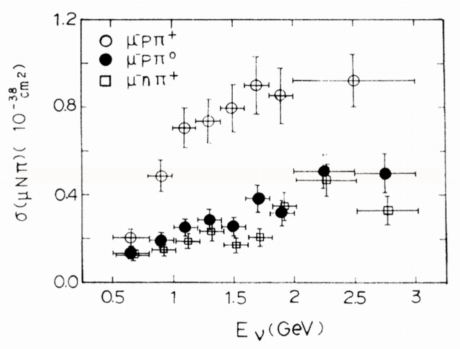
Charged-current single π^0 production in nuclei is modeled as a decay of nucleon excitations, as well as other processes like charge exchange.

Final state interactions and nuclear structure models are important to understand single π^0 production inside the nucleus.

More data means more tools to test these models.

Results on neutrino π^0 production

Neutrino-induced π^0 production in deuterium
T. Kitagaki, et al., Phys. Rev. D. 34 (1986) 2554

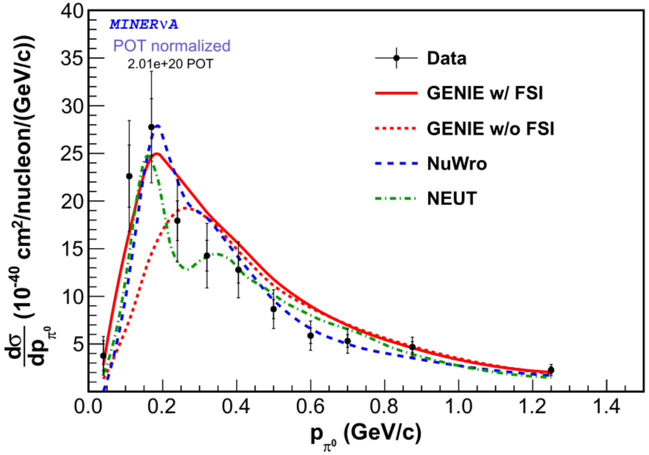


Measurements of π^0 production by neutrinos have been done since mid-80s, in deuterium bubble chambers for energies up to 3 GeV.

MiniBooNE published differential cross sections in mineral oil (CH_2) target for lower energies, up to 1 GeV.

Complementary measurements were done by SciBooNE using plastic scintillator (CH).

CC1π^0 differential cross section as function of π^0 momentum
T. Le, et al. (MINERνA collaboration), Phys. Lett. B. 749 (2015) 130-136

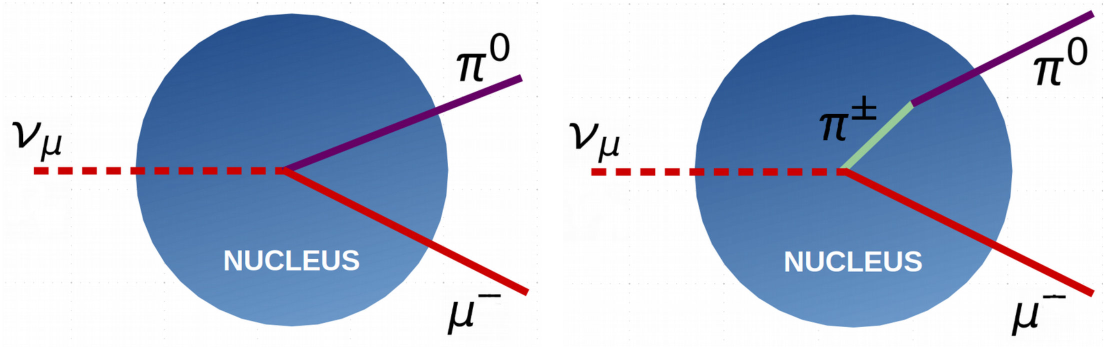


MINERνA has recently published results of charged-current 1π^0 production, using antineutrino beam of 3.6 GeV and a plastic scintillator target.

Next step includes measuring 1π^0 production at higher energies in heavy targets like iron and lead.

Goal is to calculate both differential and absolute cross sections.

Neutrino CC1π^0 production studies: signal definition



$$\nu_\mu + N \rightarrow \mu^- + \pi^0 + X$$

One and only one π^0

Negative muon in the final state

No other mesons allowed, but it can contain any baryons

Signal is defined as:

- Final state including a muon and <u>**only one**</u> π^0 produced inside the nucleus either way:
  - Directly from the neutrino interaction
  - Through $\pi^\pm$ charge exchange process
- No other mesons allowed in the final state, but there's no restriction for baryons.

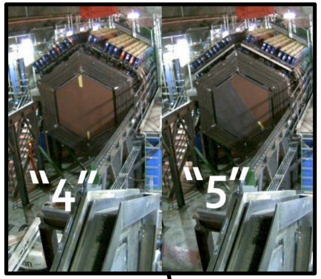
Same signal used by MINERνA before, but with a slight change.

I'm using NuMI <u>**neutrino beam**</u> with energy of <u>**6 GeV**</u> ("medium energy" configuration), as opposed to the "low energy" antineutrino beam used before.

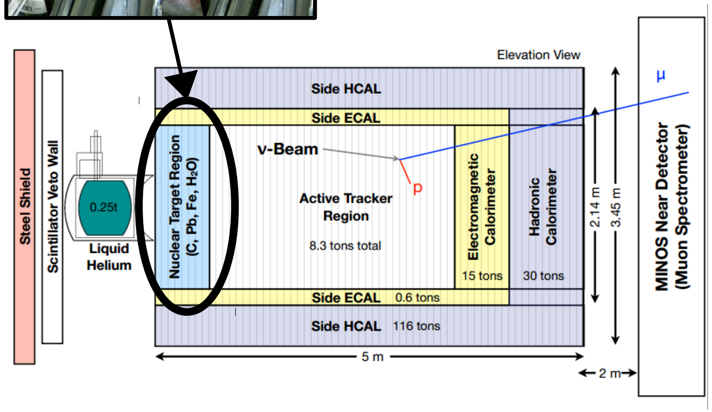
More beam energy means more intensity, and studying neutrinos allows cross section comparisons with antineutrino results.

Neutrino $CC1\pi^0$ production studies: event topology

In contrast to MINERνA's previous $CC1\pi^0$ cross section results in plastic scintillator, this time neutrinos are required to interact with heavy nuclei targets, specifically targets 4 (only Pb) and 5 (Pb and Fe).



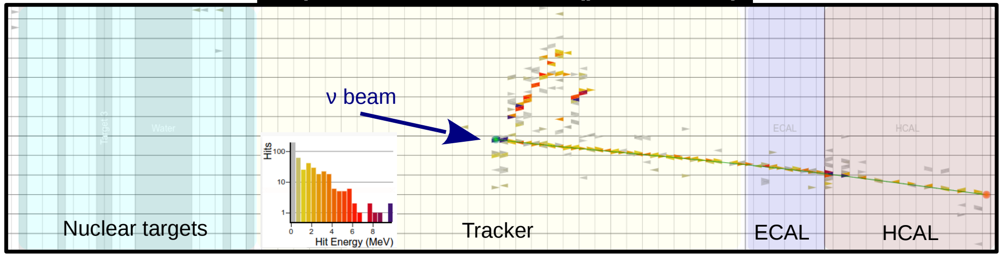
The motivation lies in looking at the event rate as well as the energy response in regions where there's a strong presence of passive material.



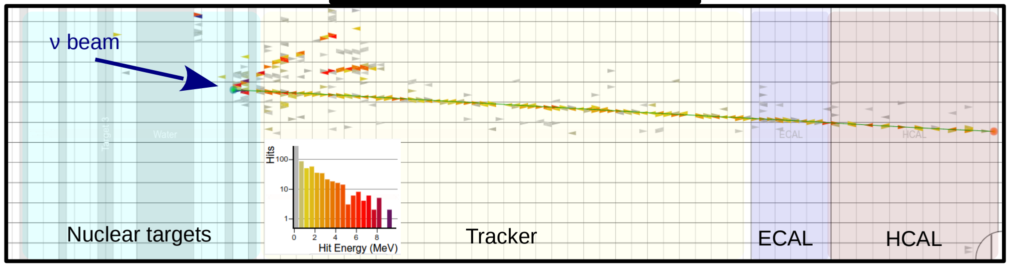
A signal event is characterized by a long noticeable μ^- track going out from the interaction vertex.

Due to the its short lifetime (~10^{-16} s), the π^0 quickly decays into two photons that have no visible track but convert into electron-positron pairs, which leave energy depositions on the active material in the form of **hits**.

π^0 produced in the tracker (plastic scint.)



π^0 produced in target 4 (Pb)



Photon reconstruction: ConeBlobs

Inside the detector, hits are grouped in **clusters**. But clusters can be due to either, π^0 decay or any other nearby activity.

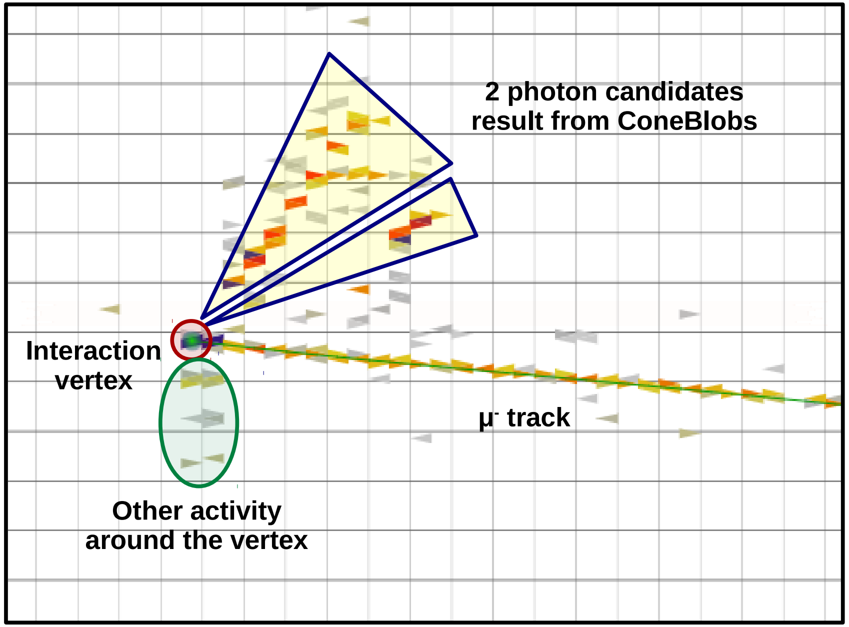
The challenge of reconstructing real $\pi^0 \rightarrow \gamma\gamma$ events lies in the correct identification of electron-positron clusters coming from the daugher photons.

The algorithm in charge of photon reconstruction is called **ConeBlobs**, using an angle scan selection:

- It gets an angular distribution of clusters around the vertex and selects those under the peaks.
- For each of cluster selected, it looks for those separated no more than 1 cm in adjacent planes.
- Clusters that satisfy these conditions are stored in an object named **blob**.

For each angle scan, <u>**ConeBlobs stores only 2 blobs**</u>, which are the two photon candidates coming from the decay $\pi^0 \rightarrow \gamma\gamma$.

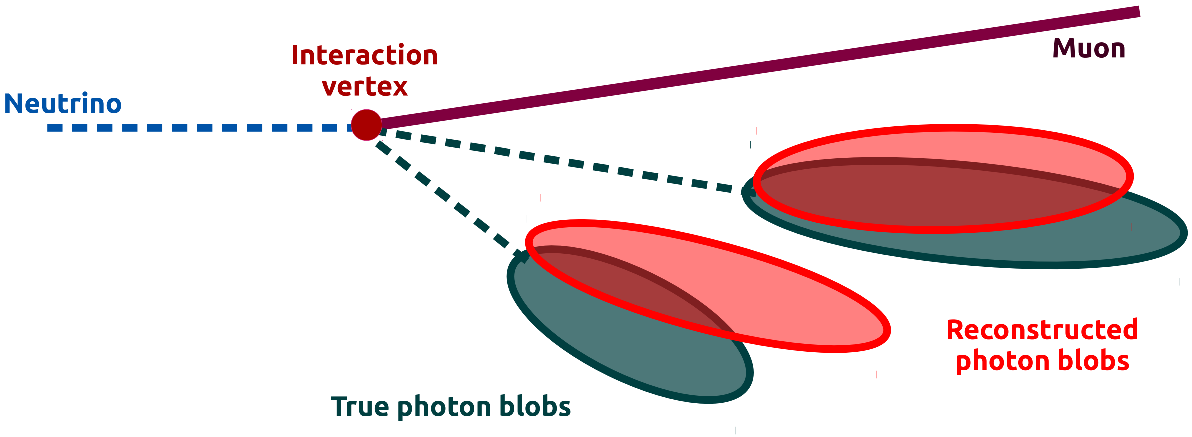
Photon with larger energy is called leading; and the other one, secondary.



Blob efficiency and purity

Photon reconstruction can identify non-π^0 clusters as candidates, or neglect real π^0 clusters. One way to verify the quality of the is looking into the **blob efficiency** and **blob purity**.

I simulated neutrino interactions in the MINERνA detector, selected signal events, and subjected them to reconstruction with ConeBlobs.



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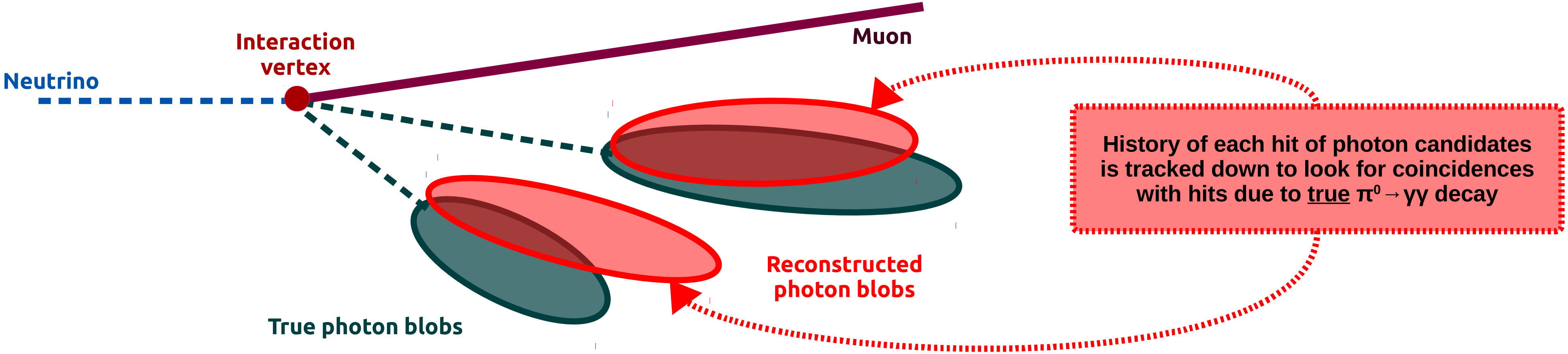
The history of each of the hits of the photon candidates is tracked down to verify if they come from true $\pi^0 \rightarrow \gamma\gamma$ decay.



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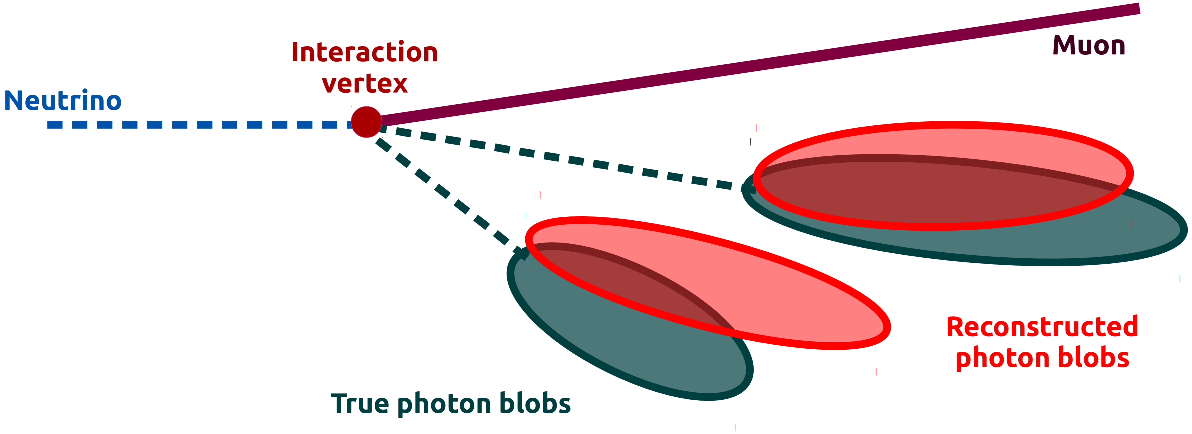
With all the information gathered, efficiency and purity are calculated in the following way:



$$\text{Blob efficiency} = \frac{\text{Energy of true } \pi^0 \text{ hits inside reconstructed blobs}}{\text{Energy of true } \pi^0 \text{ hits}}$$

$$\text{Blob purity} = \frac{\text{Energy of true } \pi^0 \text{ hits inside reconstructed blobs}}{\text{Energy of all hits inside reconstructed blobs}}$$

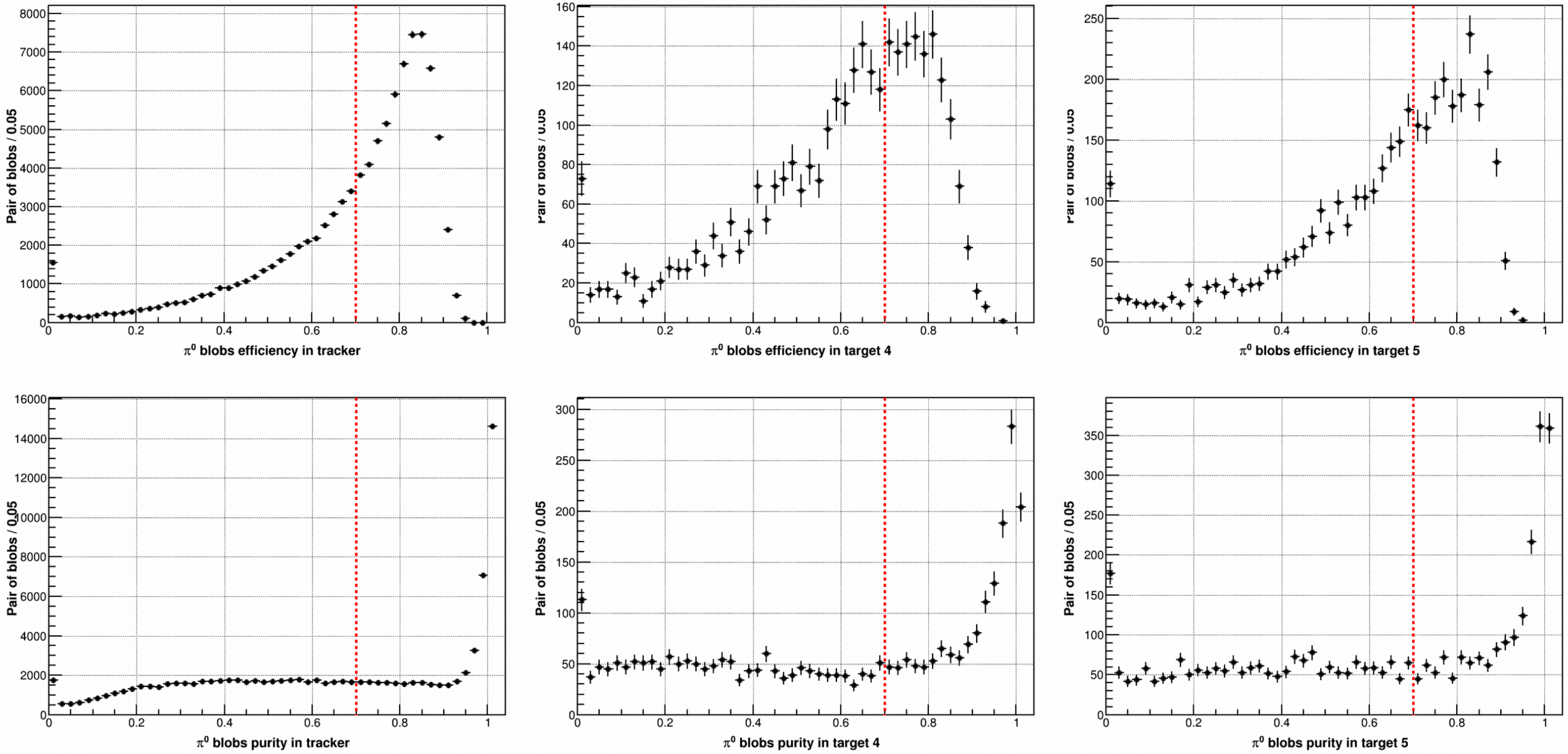
Blob efficiency and purity

These are blob efficiencies and purities for simulated events with **interaction vertex** in the **tracker**, **target 4 (Pb)** and **target 5 (Pb and Fe)**:

Tracker (plastic scint.) | Target 4 (Pb) | Target 5 (Pb and Fe)

Efficiency

Purity



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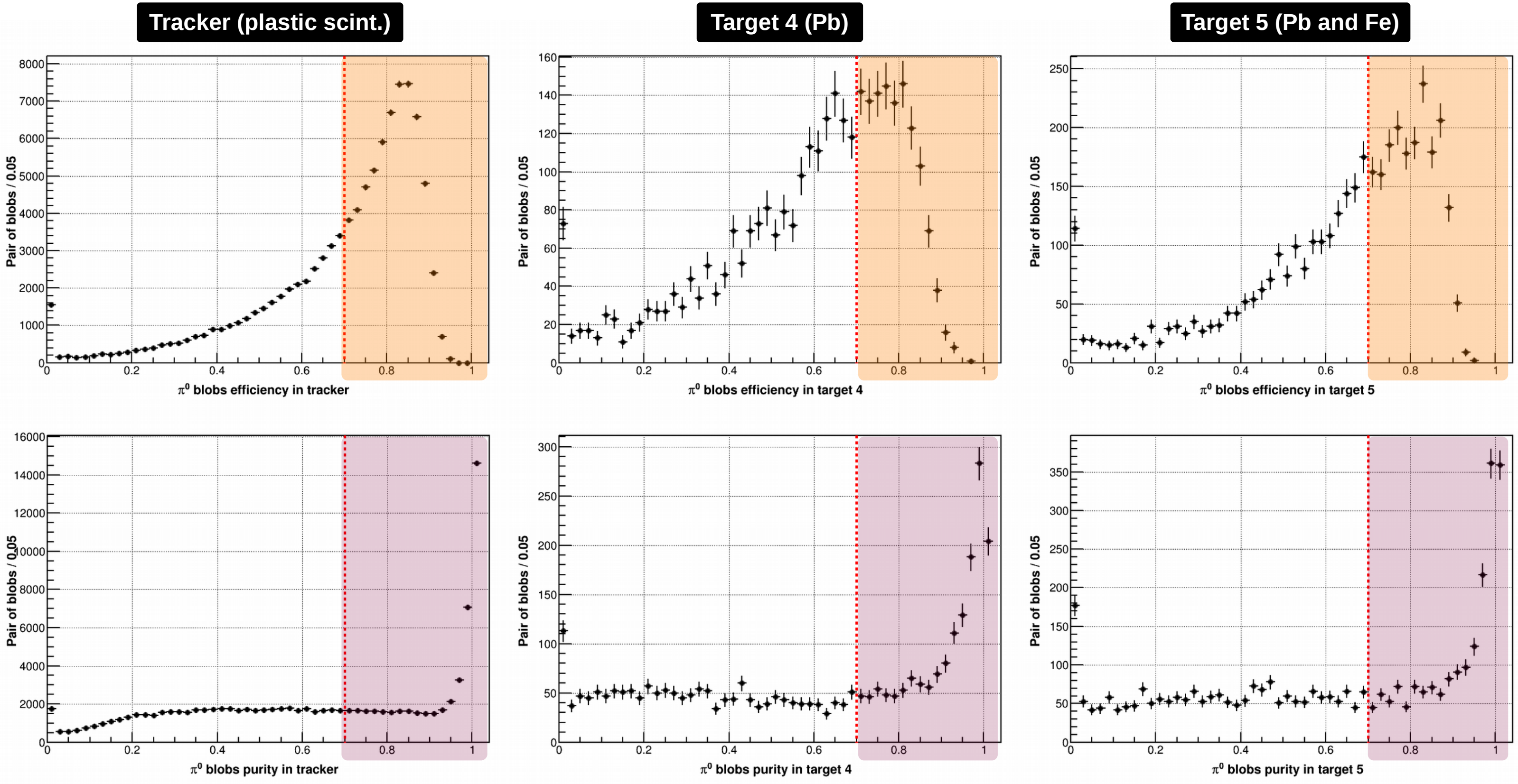


> 70% efficiency

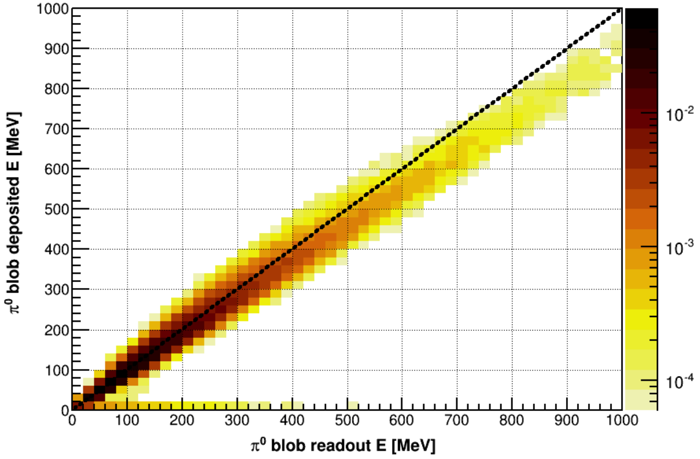
> 70% purity

π^0 energy response in active material

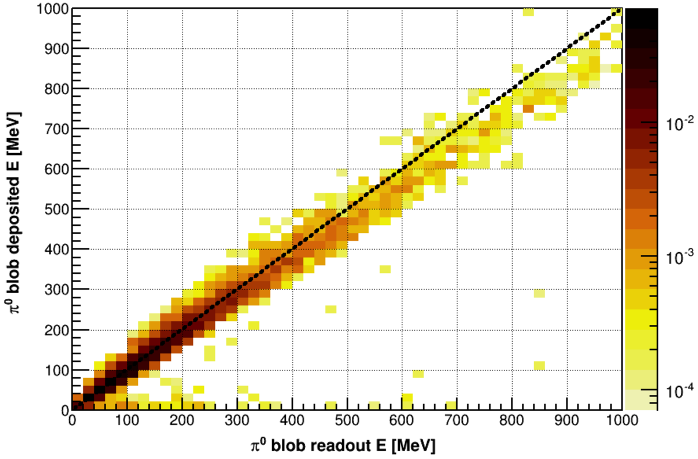
My first step in the CC1π^0 analysis in "medium energy" was to look at the π^0 energy response in active material by looking at both types of low-level blob energies we have in the simulation:

- **<u>Deposited energy</u>:** Fraction of true π^0 energy deposited on active material in the form of hits
- **<u>Readout energy</u>:** Energy obtained after the electronic readout of all hits reconstructed as π^0 energy depositions

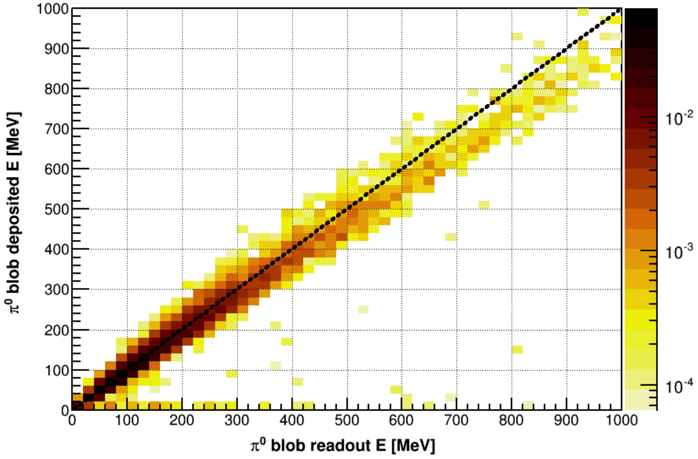
Tracker (plastic scint.)



Target 4 (Pb)



Target 5 (Pb and Fe)



π^0 energy response in active material

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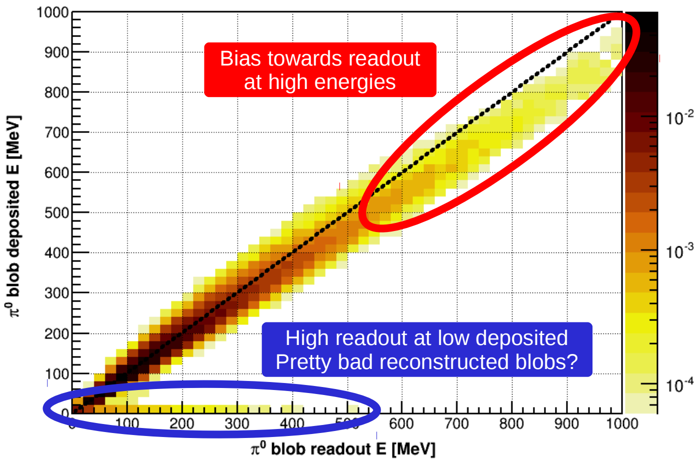
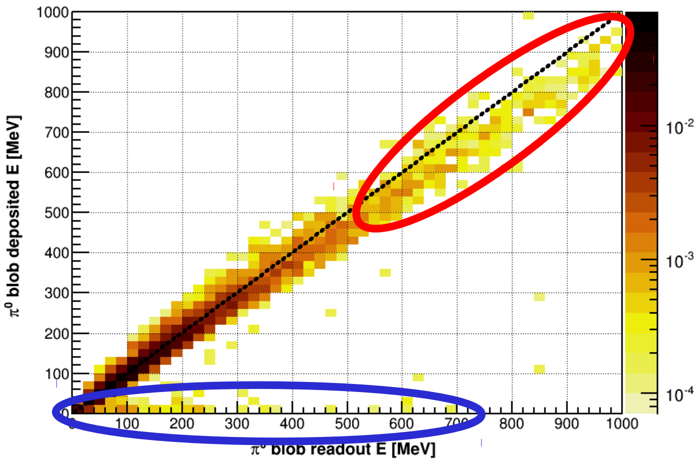
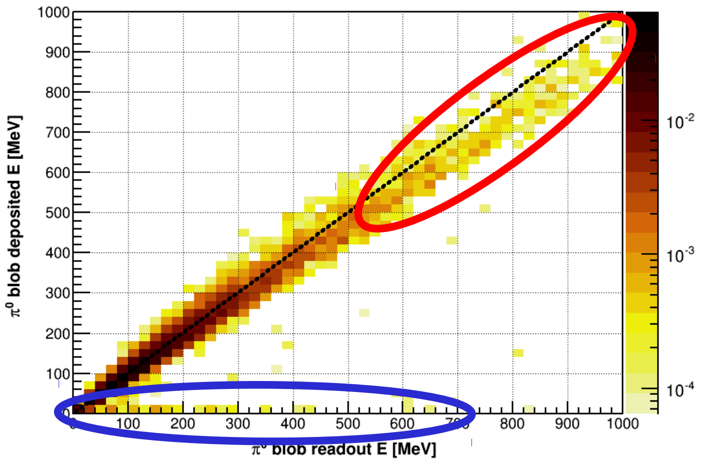


Target 4 (Pb)



Target 5 (Pb and Fe)



π^0 energy response in active material (after blob efficiency and purity cuts)

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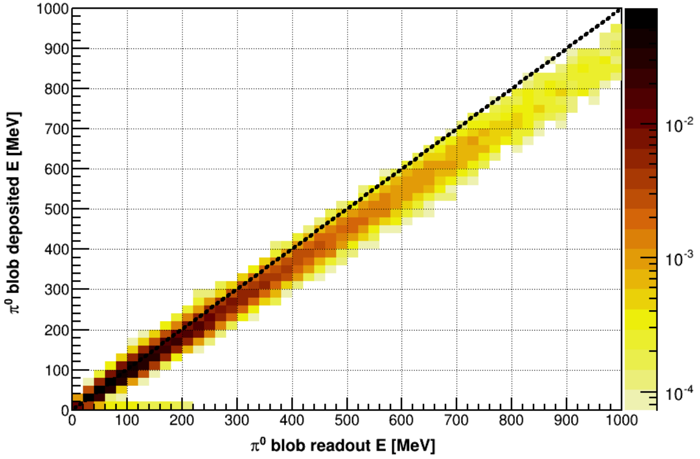
> 70% efficiency

> 70% purity

Tracker (plastic scint.)



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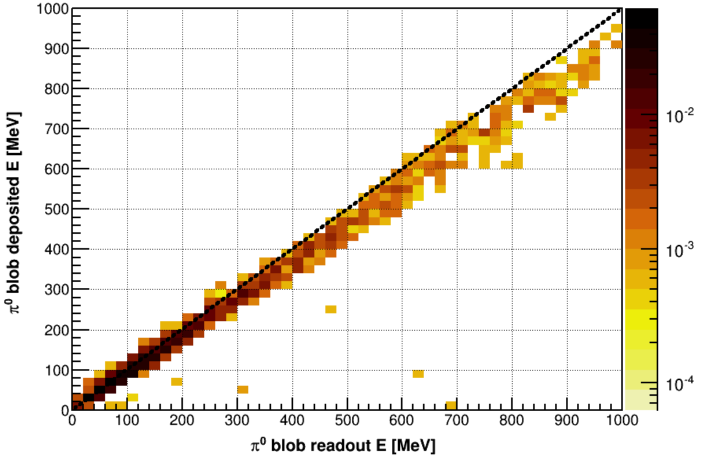
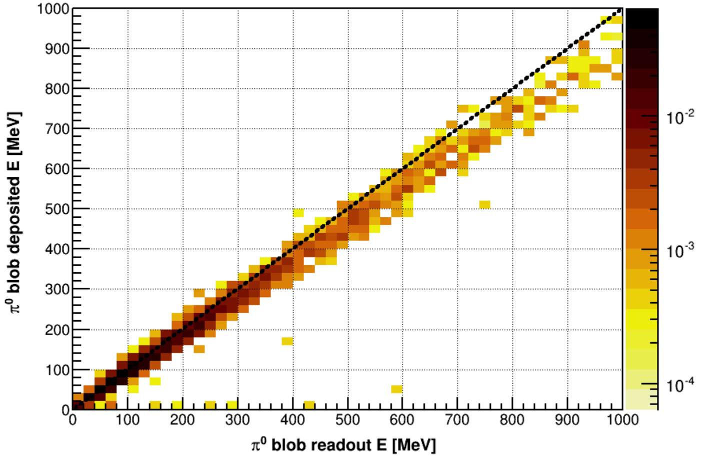


Target 5 (Pb and Fe)



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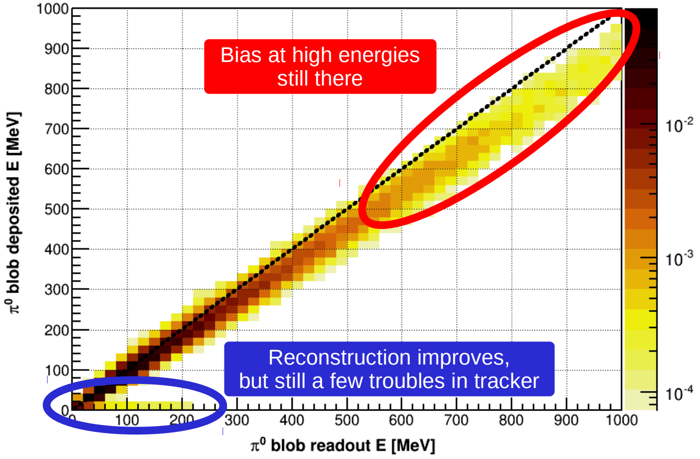
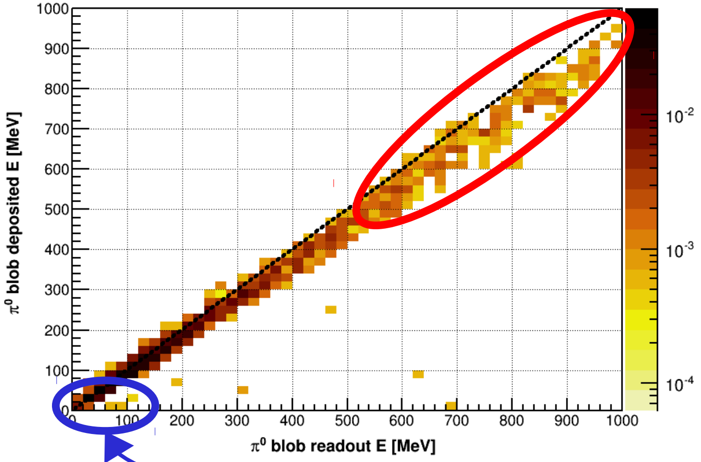
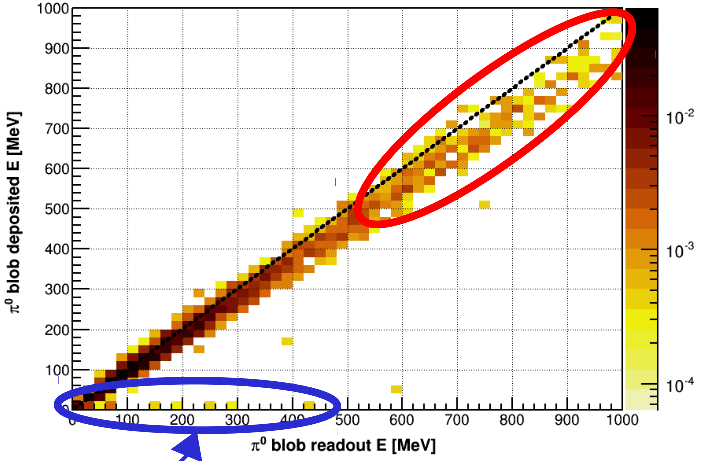


Target 4 (Pb)



Target 5 (Pb and Fe)



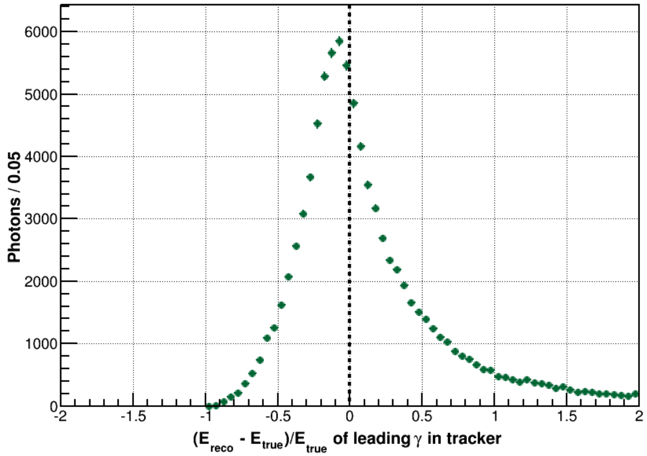
In heavy targets, it looks better

Effect on leading γ energy resolution

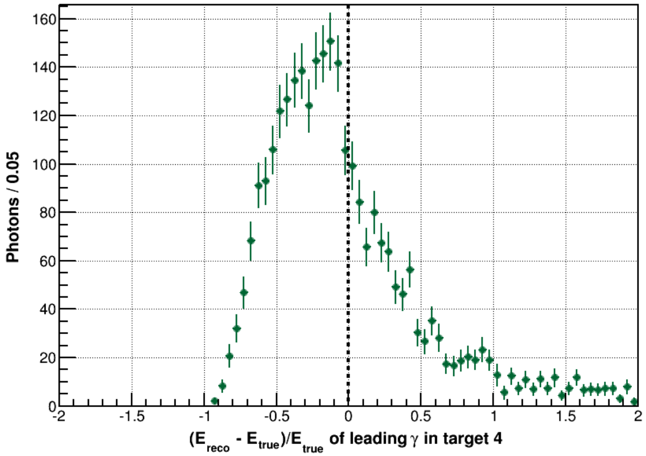
Energy resolution is defined as: $\text{Photon energy resolution} = \frac{E_{reco} - E_{true}}{E_{true}}$

where E_{reco} is the readout energy multiplied by calorimetric constants and E_{true} is the total γ energy after the π^0 decay.

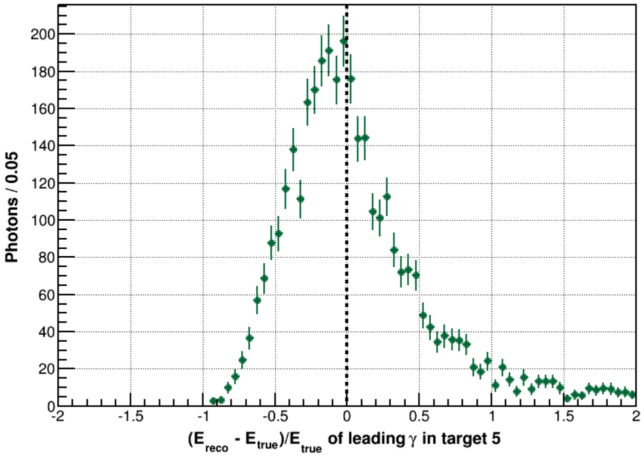
Tracker (plastic scint.)



Target 4 (Pb)



Target 5 (Pb and Fe)



Effect on leading γ energy resolution (after blob efficiency and purity cuts)

> 70% efficiency

> 70% purity

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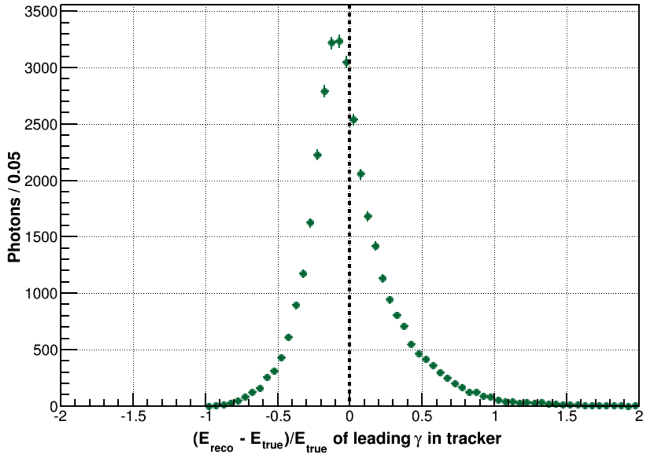
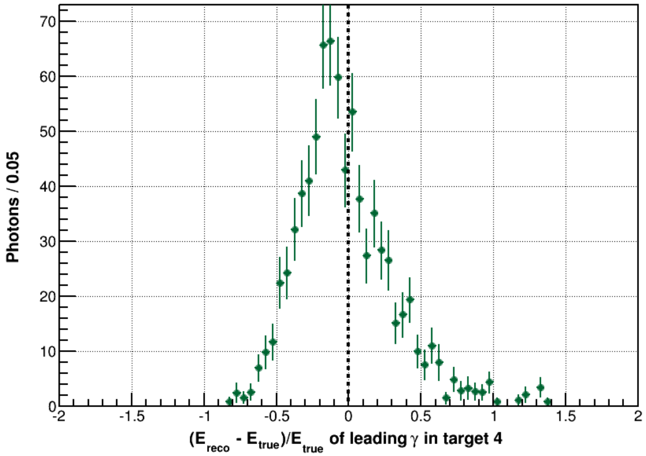
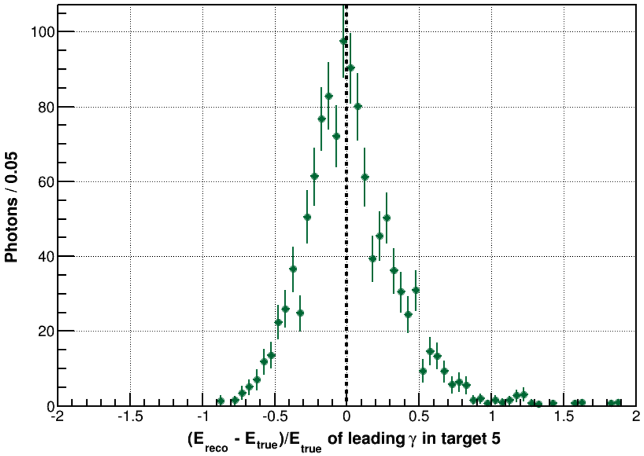


Target 4 (Pb)



Target 5 (Pb and Fe)

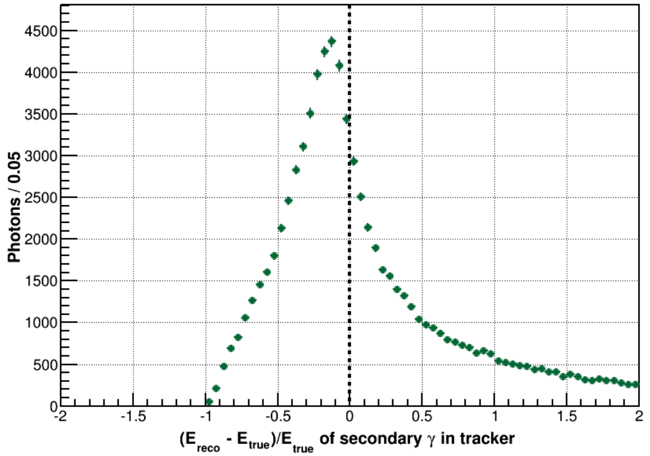


Effect on secondary γ energy resolution

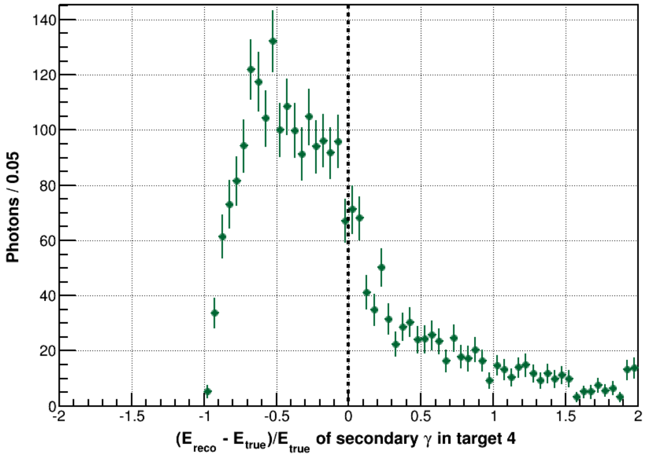
Energy resolution is defined as: **Photon energy resolution** $= \dfrac{E_{reco} - E_{true}}{E_{true}}$

where $\mathbf{E}_{reco}$ is the readout energy multiplied by calorimetric constants and $\mathbf{E}_{true}$ is the total γ energy after the π^0 decay.

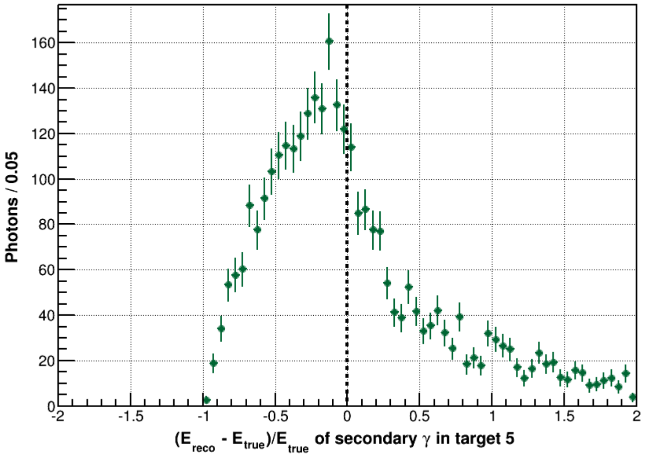
Tracker (plastic scint.)



Target 4 (Pb)



Target 5 (Pb and Fe)



Effect on <u>secondary</u> γ energy resolution (after blob efficiency and purity cuts)

> 70% efficiency

> 70% purity

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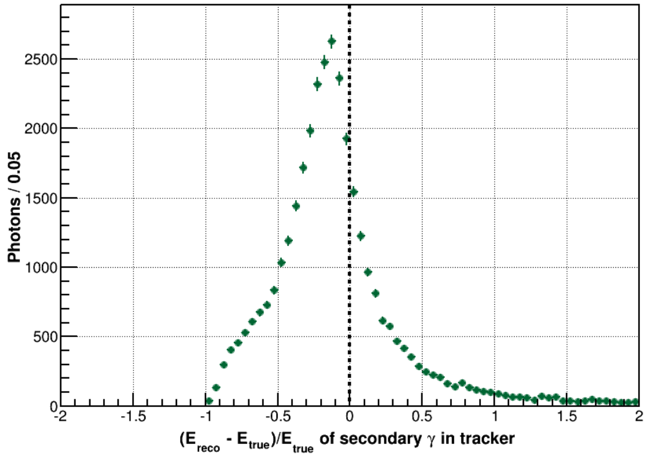
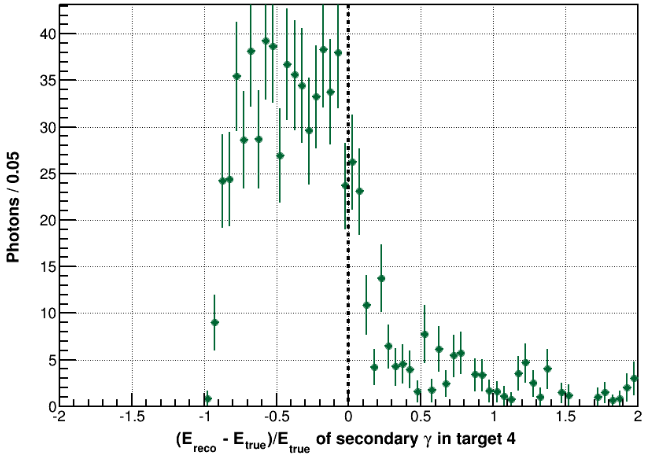
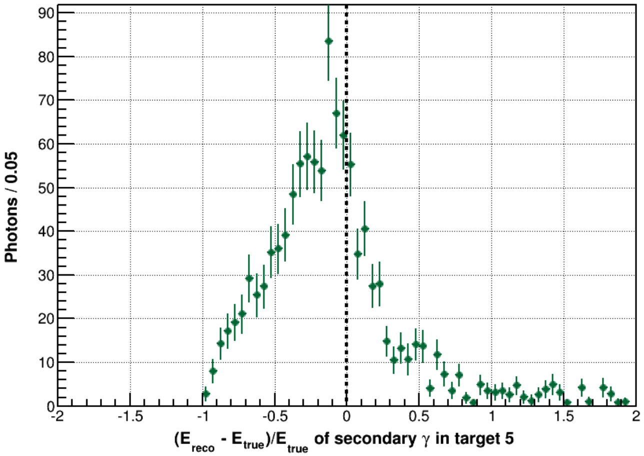
Tracker (plastic scint.)



Target 4 (Pb)



Target 5 (Pb and Fe)



Conclusions

- Blob efficiency and purity of π^0 events from the tracker region look reasonable. However, efficiency in targets 4 and 5 don't. I have two hypotheses:
  - Photons convert and deposit energy mostly inside target 4 (full Pb) whose thickness is about 1 interaction length.
  - Photons can't deposit energy in active material downstream target 4 since target 5 (Pb and Fe) absorbs most of that energy.
- As a consequence of the last point, energy resolution of secondary photon of target 4 and 5, especially the former one, looks bad.

$$\text{Blob efficiency} = \frac{\text{Energy of true } \pi^0 \text{ hits inside reconstructed blobs}}{\text{Energy of true } \pi^0 \text{ hits}}$$

$$\text{Blob purity} = \frac{\text{Energy of true } \pi^0 \text{ hits inside reconstructed blobs}}{\text{Energy of all hits inside reconstructed blobs}}$$

- The bias towards π^0 readout energy respect to true deposited energy needs more understanding.
- The goal of this study was to show the current low-level characterization of $1\pi^0$ events using a "medium energy" beam. The first steps were fine, but it still needs improvements for future goals towards a precise measurement of A-dependent neutrino cross sections.

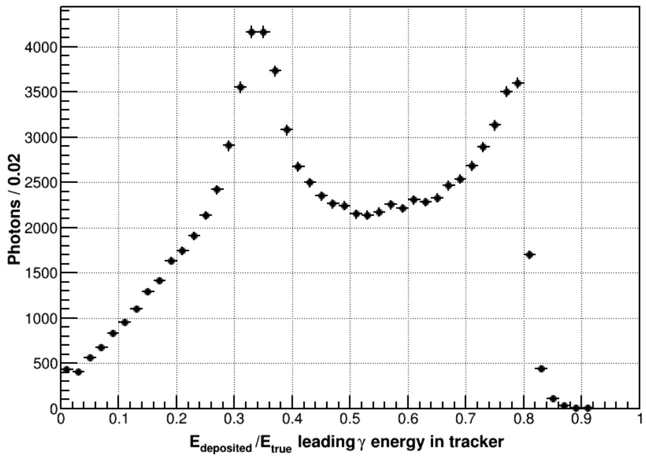
Thank you!

Backup slides

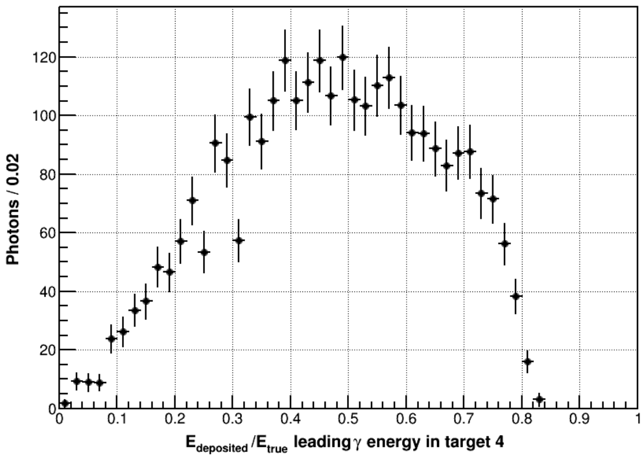
Fraction of true <u>leading</u> γ energy deposited on active material

This is the ratio between the **<u>deposited photon energy</u>** in active material and the **<u>true photon energy</u>**.

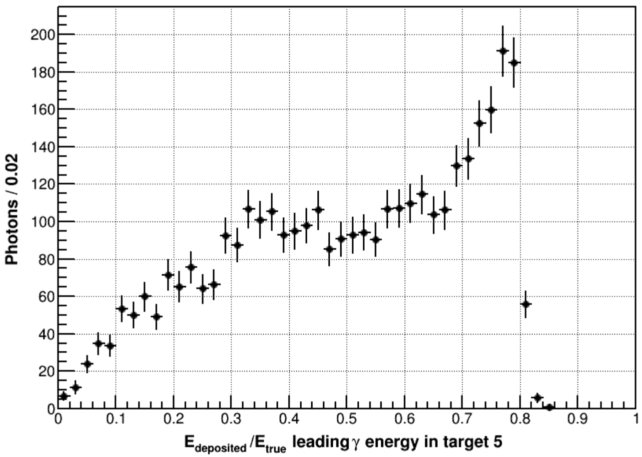
Tracker (plastic scint.)



Target 4 (Pb)



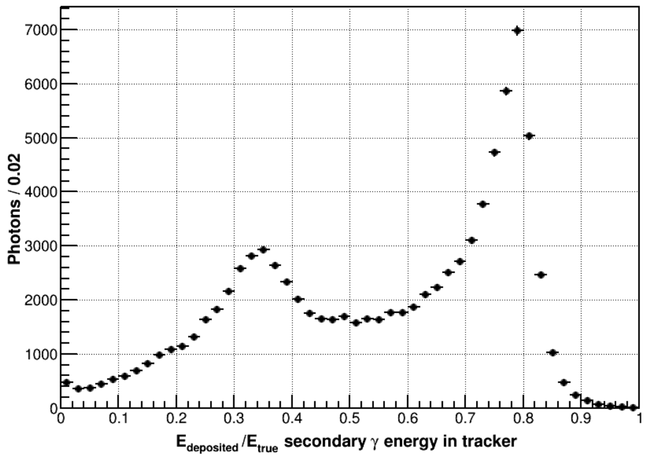
Target 5 (Pb and Fe)



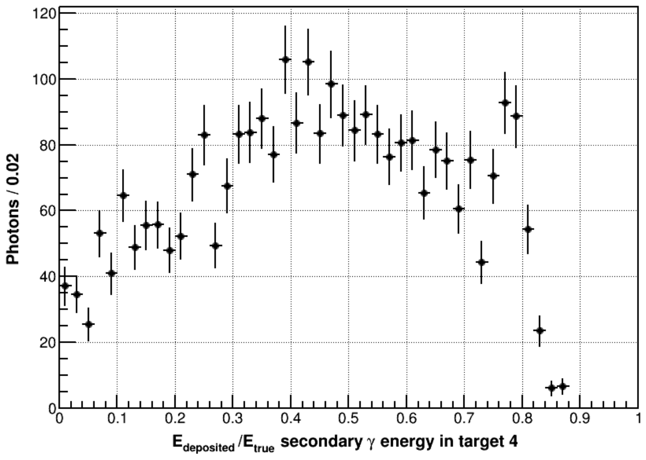
Fraction of true secondary γ energy deposited on active material

This is the ratio between the **deposited photon energy** in active material and the **true photon energy**.

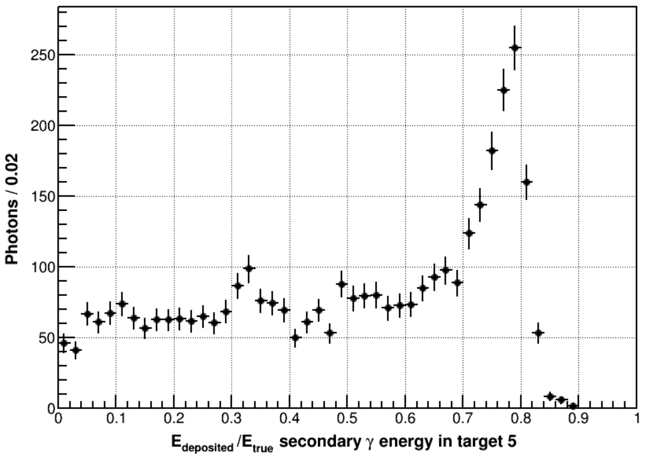
Tracker (plastic scint.)



Target 4 (Pb)

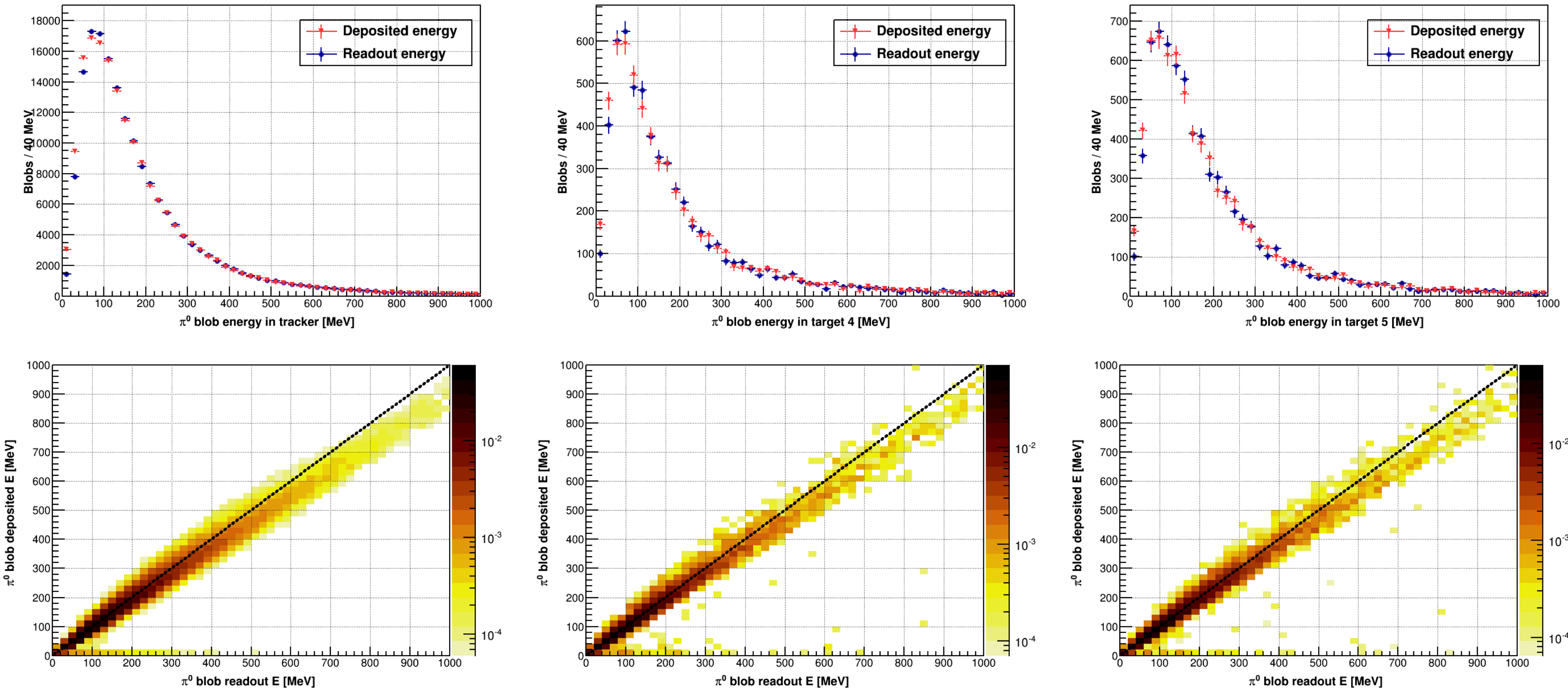


Target 5 (Pb and Fe)

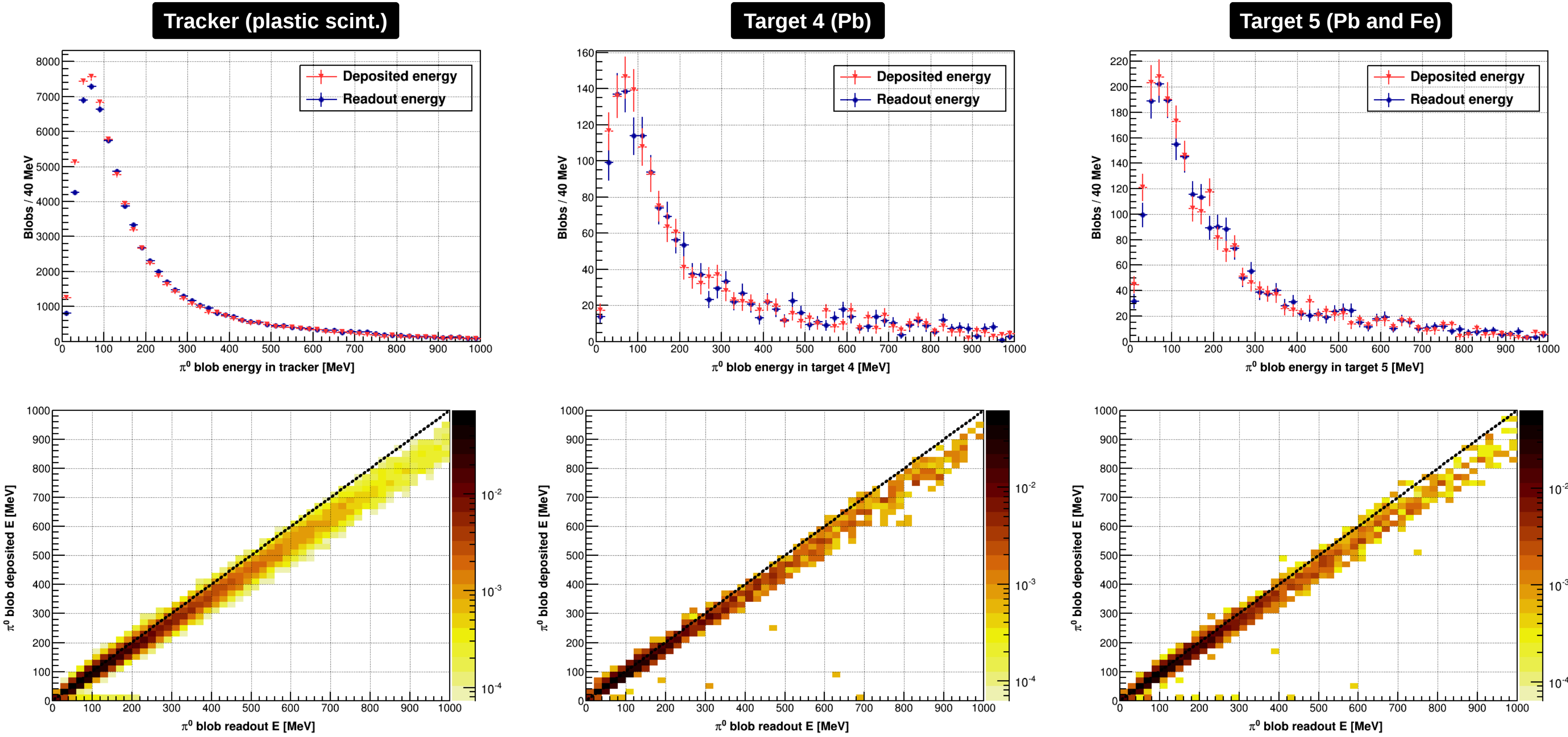


π^0 energy response in active material

Tracker (plastic scint.) | Target 4 (Pb) | Target 5 (Pb and Fe)



π^0 energy response in active material (after efficiency and purity cuts)



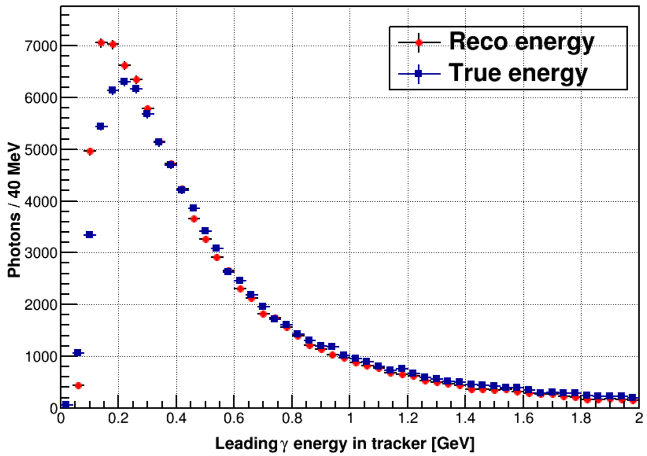
> 70% efficiency

> 70% purity

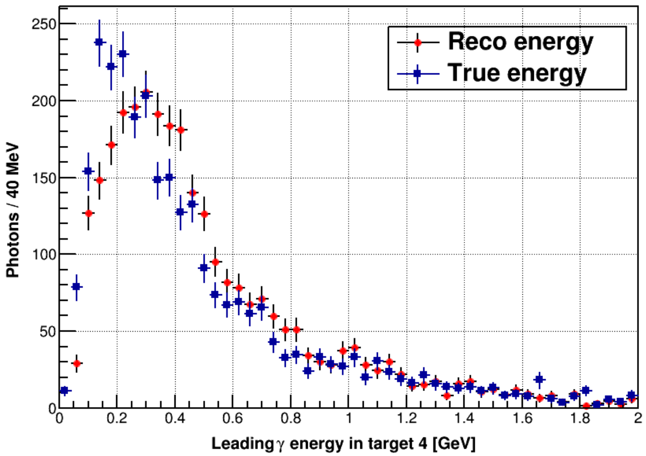
True and reco leading γ energy

- **True energy**: Photon energy after π^0 decay.
- **Reco energy**: Photon energy obtained from readout after applying calorimetry.

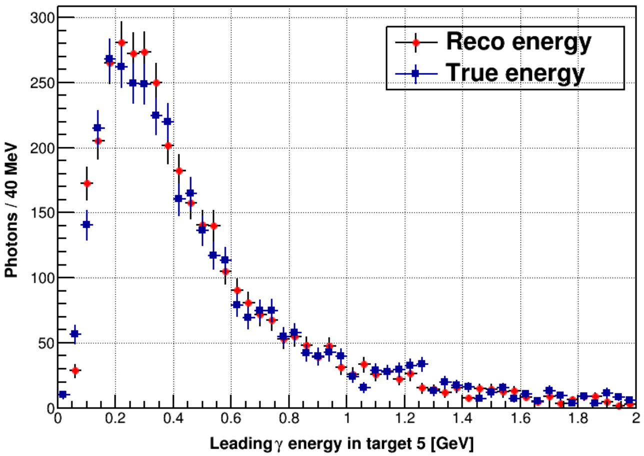
Tracker (plastic scint.)



Target 4 (Pb)



Target 5 (Pb and Fe)



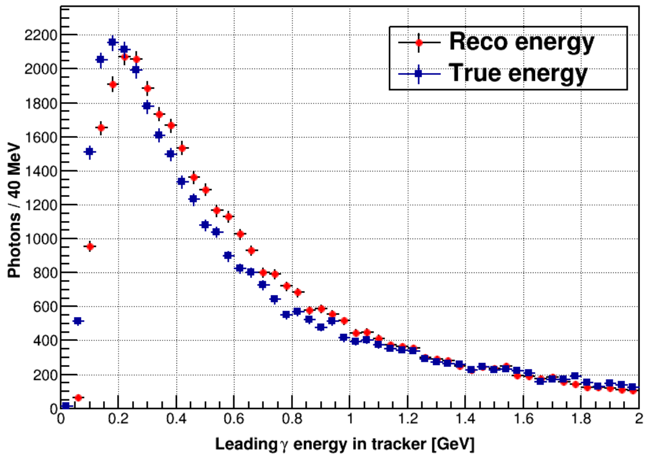
True and reco leading γ energy (after blob efficiency and purity cuts)

> 70% efficiency

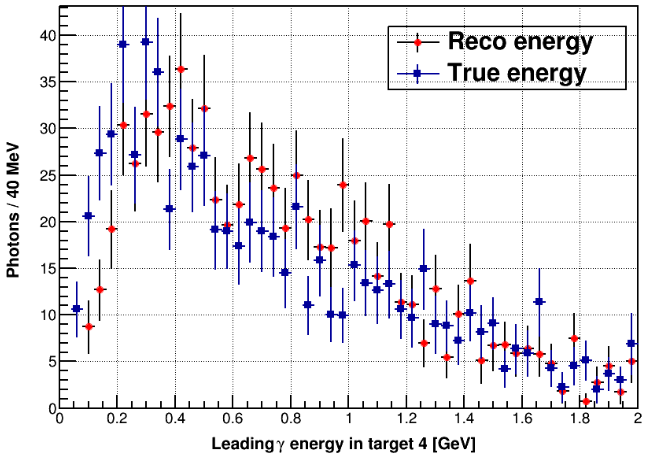
> 70% purity

- **True energy**: Photon energy after π^0 decay.
- **Reco energy**: Photon energy obtained from readout after applying calorimetry.

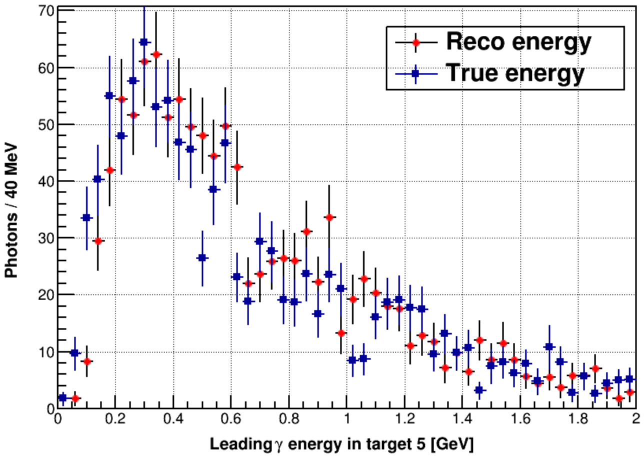
Tracker (plastic scint.)



Target 4 (Pb)



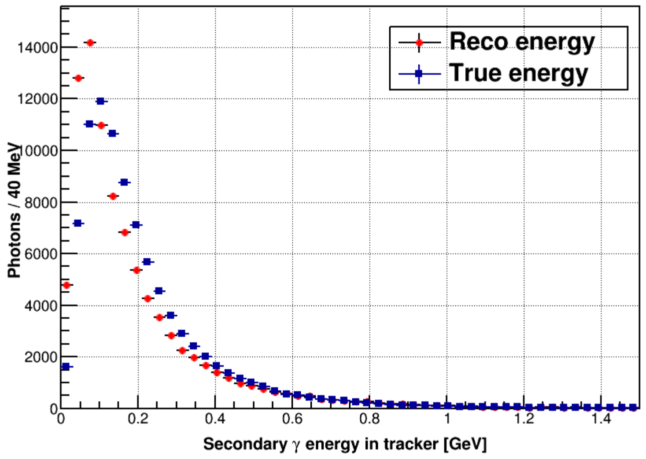
Target 5 (Pb and Fe)



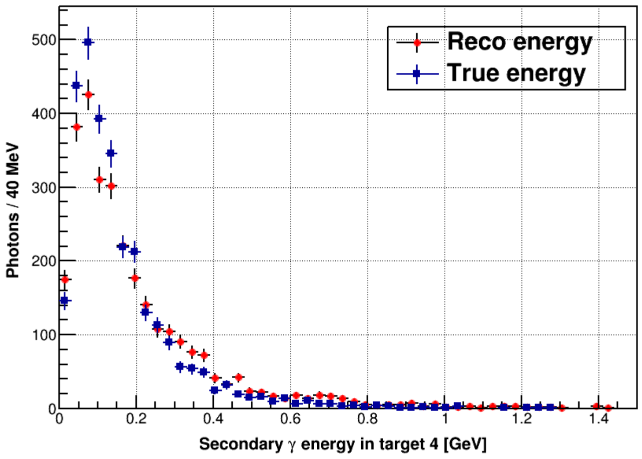
True and reco secondary γ energy

- **True energy**: Photon energy after π^0 decay.
- **Reco energy**: Photon energy obtained from readout after applying calorimetry.

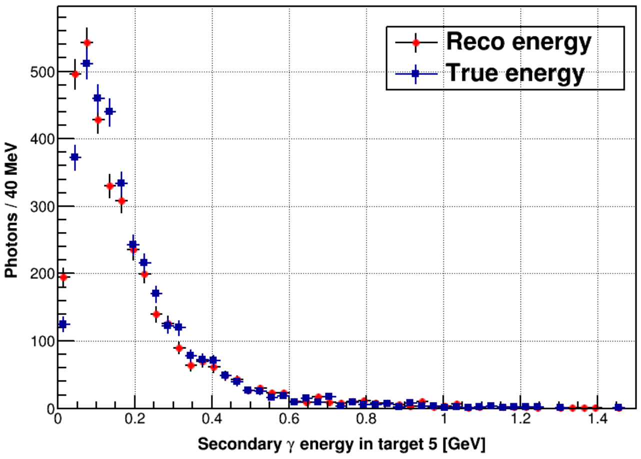
Tracker (plastic scint.)



Target 4 (Pb)



Target 5 (Pb and Fe)



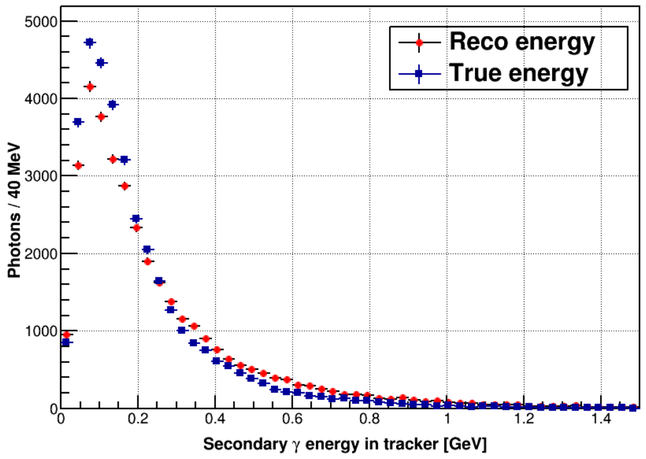
True and reco secondary γ energy (after blob efficiency and purity cuts)

- **True energy**: Photon energy after π^0 decay.
- **Reco energy**: Photon energy obtained from readout after applying calorimetry.

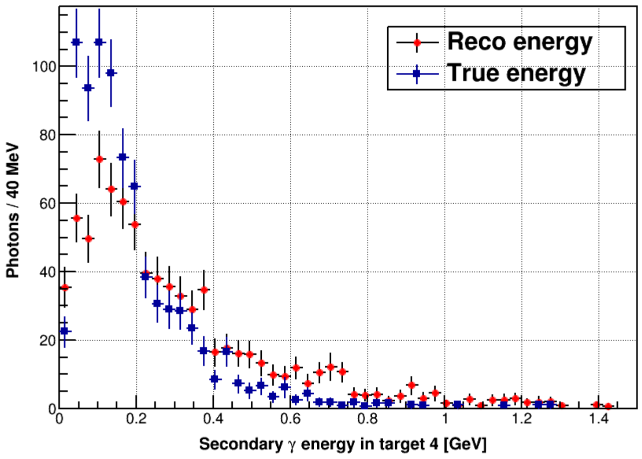
> 70% efficiency

> 70% purity

Tracker (plastic scint.)



Target 4 (Pb)



Target 5 (Pb and Fe)